

MODELING COCKPIT INTERFACE USAGE DURING LUNAR LANDING REDESIGNATION

Zarrin K. Chua
Georgia Institute of Technology
Atlanta, Georgia

Laura M. Major
Charles Stark Draper Laboratory
Cambridge, Massachusetts

Karen M. Feigh
Georgia Institute of Technology
Atlanta, Georgia

Fulfilling NASA's space exploration objectives requires precision landing to reach lunar sites of interest. During the approach and landing stages, a landing point redesignation (LPR) display will provide information to the crew regarding the characteristics of alternate touchdown points. Building on a previous study which examined crew tasks during LPR but did not account for the specialized behavior of experts, this investigation will present a new task sequence model, specific to expert decision-making. This analysis furthers the development of a predictive task execution model, which is used to test the efficacy of alternate information display and operator actuator design concepts. The task model and cockpit display recommendations presented in this study provide a significant improvement in LPR task execution time. This paper examines the task sequence during lunar landing, describes the predictive task execution process model, and recommends cockpit display requirements for effective decision making.

During Apollo missions the astronauts were required to land near a predetermined lunar site to achieve national and scientific mission objectives. Safe landing was achievable through certification of the area prior to flight, providing adequate safe landing areas. Future lunar missions place an even greater emphasis on complete lunar surface accessibility and precision landing at sites of interest (Brady, Schwartz & Straube, 2006). To successfully reach these goals, future lunar-bound astronauts will be aided by an Autonomous Flight Manager (AFM) and a set of displays to assist the crew in performing complex and critical tasks during landing. During the landing point redesignation (LPR) task, crucial information will be provided to the crew on the LPR display by translating raw sensor data (from a LIDAR) into information required to support crew decision making. The focus of this study is to improve the design of a display to facilitate crew cognitive processes during LPR. Specifically, this paper examines the task sequence during the LPR task, describes a predictive task execution process model, and recommends cockpit display design requirements to ensure effective decision making.

Model Description

Task Sequence

This work builds on a previous study (Chua & Major, 2009) which examined crew tasks during LPR but did not incorporate the behavior of experts. Experts react differently than novices, especially in time critical, high-stakes situations. Experts look for cues and patterns to determine the course of action to achieve an objective (Klein, 1998), rarely following a linear approach. Klein's theory of recognition-primed decision making (RPD) asserts that mental simulation is used to predict the outcomes of considered options. These options are evaluated as they are formed, rather than brainstormed *en masse* and eliminated individually. The decision making process usually ends once a satisfactory solution is obtained, rather than continuing until a perfect solution is reached.

The RPD theory applies to the initial stages of the LPR task. The previous task model included explicit cognitive steps for the crew to examine each set of hazards and landing aim point (LAP) recommendations individually (Chua & Major, 2009). However, applying RPD, one can predict that the crew would look for large scale patterns in the terrain and quickly determine if the location of the LAPs matched expected terrain patterns. The predicted behavior was further supported by a representative from the NASA Crew Office, who confirmed that the crew will most likely look for identifiable terrain markers (ITMs) to quickly assess the situation, and then make a rapid decision on the suitability of the LAPs given the situation. This behavior is also consistent with the Apollo missions, in which the astronauts were trained to identify specific patterns in the terrain, such as the "Snowman" configuration of several large craters during Apollo 12 (Manned Spacecraft Center, 1970). The recognition task during Apollo required more time than the anticipated execution of future landings because the Apollo decision aid (Landing Point Designator, LPD) was less sophisticated than what can be provided today. Apollo's LPD required several manual steps to first obtain the landing site location before identifying that site out the window.

Based on these insights, an LPR task model was developed for this study by building upon the generic model from Chua and Major (2009). The new LPR task model utilizes RPD theory, where the analysis is non-linear and includes attempting to match environmental cues to expectancies and only performing a detailed analysis

if the cues are different, in orientation and in form, than what is expected. This task sequence is illustrated in Figure 1, with the RPD loop highlighted in green.

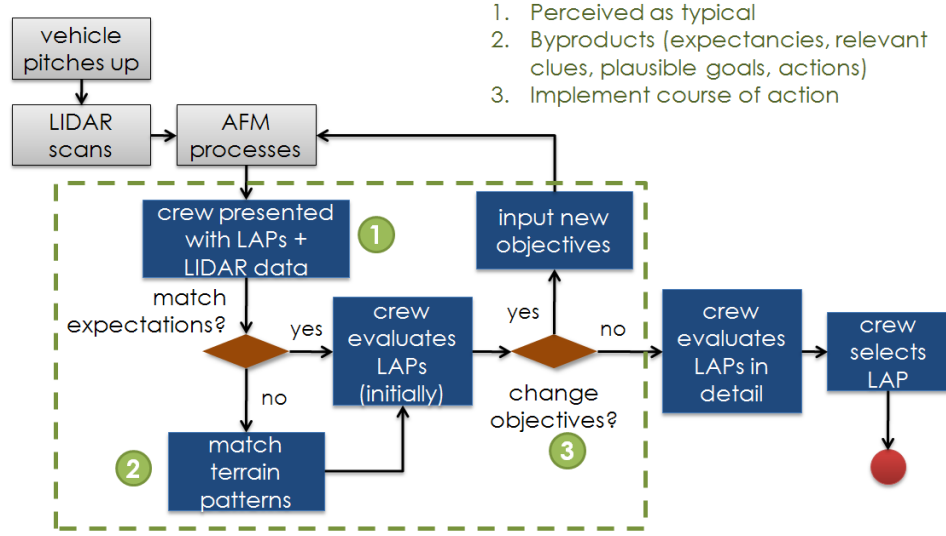


Figure 1. Landing point redesignation task sequence. The dark boxes are within the scope of this investigation.

Two major modifications were made to the LPR task sequence model described by Chua and Major (2009). First, a subtask is added prior to the initial evaluation of the LAPs. The previous model neglected the steps required to develop an overall understanding of the landing site and assumed that these steps would be completed prior to the LIDAR scan. This modification, based on the first phase of RPD theory, provides an estimate of the subtasks required to initially evaluate the landing site, especially in the event of unexpected terrain. Second, the detailed evaluation of the LAPs is revised to account for expert behavior. The previous model assumed astronauts would potentially evaluate every combination of alternative LAPs (based on the capabilities of the display design). While this calculation is acceptable for computing maximum times of expected task completion, RPD and the input provided by a Crew Office representative, are used to refine this assumption and enable more accurate time estimates. This modification places a limitation on the number of landing sites presented.

Once presented with the processed LIDAR data and the AFM information (hazard areas, LAP recommendations), the crew first performs a high level evaluation of the cues (terrain patterns and LAP recommendations), to determine whether the situation is what they expect or not. If the situation does not match their expectations, the crew will then further evaluate the terrain. If the scenario is nominal, the crew will typically proceed to evaluate the LAP options. Each of these distinct tasks (marked by dark boxes in Figure 1) is decomposed into smaller primitive tasks, using the KLM-GOMS (Card, Moran, and Newell, 1983; Olsen and Olsen, 1990). In addition to the tasks decomposed by the original model, the new model includes the new task of terrain pattern recognition, the location of LAPs, and a specific operator actuator for communicating objective changes to the AFM.

Predictive Task Execution Time Model

The predictive task execution process model provides an estimation of time to complete the LPR task based on the astronaut strategy and the mission scenario. This model is essentially a summation of the primitive operators associated with the LPR task sequence, as determined using the decomposition scheme described by Card, Moran, and Newell (1983) in the KLM-GOMS theory. This model also uses the secondary primitive operators in the Chua and Major (2008) study, as first presented by Olsen and Olsen in 1990. These primitive operators are based on the interactions of the operator with the LPR display as described in the previous section. This model is described the relationship presented in Equation 1:

$$f(\alpha, \varepsilon, \Pi, n, H) = 2.4\varepsilon + 4.8\alpha + 2.02n + \frac{6(n+1)(H+\Pi+3)}{5} + 5.72 \quad (1)$$

where α is the number of LAPs evaluated in detail (including the baseline point); ε is the training parameter, where ε is 0 if the training is correct, 1 if the astronauts are unprepared for the actual terrain; Π is the number of points of interest (POI); n is the number of objective changes; and H is the number of ITMs. A distinction must be made

regarding hazards and ITMs. An ITM is a group of hazards that create such a shape or pattern that an astronaut regards this group as a single entity, rather than individual craters or rocks. While this formulation is capable of calculating most feasible lunar scenarios, equation 1 comes with restrictions. Input parameters such as the number of LAPs evaluated in detail and the number of objective changes is difficult to model, as they are dependent on the scenario and operator strategy. This model is better used to determine the range of potential task execution time. To generate this range of task times, the Crew Office is consulted regarding the most feasible astronaut behavior. The following three scenarios are utilized:

1. **Minimum**: Best case scenario. Expectations are matched (the lunar terrain maps used during training correctly prepared the astronauts for what they actually see); no change in objectives, and only one alternative LAP is evaluated in detail. ($\alpha = 2, \varepsilon = 0, n = 0$)
2. **Maximum**. Worst case scenario. Expectations are not matched (astronauts look for the ITM), objectives are changed twice, and all LAPs are evaluated in detail. ($\alpha = 4, \varepsilon = 1, n = 2$)
3. **Nominal**. Expectations are matched, objectives are changed once, and only two other LAPs are evaluated in detail. ($\alpha = 3, \varepsilon = 0, n = 1$)

Equation 1 can then be computed over a range of points of interest and hazards to better understand the task execution time over a variety of scenarios.

Landing Point Redesignation Display Design Recommendations

A significant challenge of LPR is the balance between crew control and inherent time constraints. The crew must be given a means to refine the desired characteristics of a LAP, but too many options can overwhelm the crew and greatly increase mental workload (Smith, McCoy & Layton, 1997). Conversely, automating the decision of a final LAP is faster, but eliminates the crew's human advantages of adaptability and creativity (Wiener & Curry, 1980). The LPR display must seamlessly integrate the static inputs of the AFM (*a priori* mission estimations, etc.), the dynamic LIDAR data and dynamic goals of the crew (based on real-time data). The quality of this integration includes the presentation of AFM information to the crew, and correspondingly, the ability of the crew to communicate goals and intent to the AFM. Unfortunately, poor designs in either can result in bottlenecks, or localized increases in crew workload. Previously, two major bottlenecks were identified using the generic LPR task sequence model. These bottlenecks pertain to factors just presented - operator actuator design (to signal an objective change intent) and presentation of decision-making information to enable detailed evaluation and selection of a final LAP from several choices.

To mitigate the first bottleneck of communicating the intent to change objectives, several operator actuator designs are considered in this research. The previous design, a combination of three slider bars and two buttons (Forest, Cohanin, & Brady, 2008), granted maximum control by allowing the crew to manually set hazard tolerances and the weighting distribution between safety, fuel efficiency, and nearness to the Point of Interest (POI). However, this operator actuator design leads to the possibility of the crew extending more effort than necessary in calibrating the tolerances and weights during the landing. Two other designs are considered: a safety buffer dial and "hot keys", a series of buttons with predefined options regarding tolerances and weighting distribution.

The safety buffer dial changes only the safety tolerance remaining a safe distance from the hazards while also as close as possible to the POI. Turning the dial in one direction would communicate a desire to increase the safety tolerance, thus leading to safer LAPs (farther from hazards, defined as areas beyond a slope and roughness tolerance). Turning in the other direction would decrease the safety tolerance, potentially presenting LAPs closer to the POI. If the dial is designed to provide some static unit/radian and a representation of feedback, the operator could sufficiently fine tune to a specific tolerance. The safety buffer dial is modeled using the KLM-GOMS methodology as a "pointing mouse" primitive operator. While the safety buffer dial is simple to use, this operator actuator is limited in dimension – the specific slope and roughness tolerances and fuel efficiency are neglected. In addition, the specific weight distribution between the top three driving objectives (safety, fuel efficiency, nearness to POI) cannot be determined. Conversely, the hot key concept provides more dimensionality than the dial, but at the cost of tolerance and weight precision.

The hot key concept presents several distinct options to the crew. Each hot key represents a fixed set of tolerances on safety and fuel efficiency and a weight distribution between safety, fuel efficiency, and nearness to POI. The exact tolerances and weight distributions can be tuned based on the mission and crew preferences. The AFM would return alternate sites based on the objective function encoded for each hot key. During the LPR task the crew can toggle between the hot keys. A set of five hot keys are included in this study and are described in Table 1. The hot keys are modeled as a push button.

Table 1. *Hot keys used in the LPR task and their definitions.*

Hot Key	Definition
Safety	The safest landing sites (farthest from hazards, conservative tolerances on slope and roughness). Fuel efficiency and nearness to POI are held equal. Example of weight distribution (on a 100 point scale): 90/5/5 or 80/10/10
Fuel	Most fuel efficient sites (typically center and forward, aft of the LIDAR scanned landing area). Safety and nearness to POI are held equal. Example of weight distribution: 5/90/5, 10/80/10
POI	Nearest to POI. This objective could be interpreted in different ways, if there are multiple POIs presented: the AFM could find aim points nearest to all POIs, or the AFM could find the closest aim points to at least one POI. This research assumes the later interpretation. Tolerances on slope and roughness are less stringent and safety and fuel efficiency are held equal. Example of weight distribution: 5/5/90, 10/10/80
Balanced	Equal, or balanced weight distribution between safety, fuel efficiency, and nearness to POI. Weight distribution: 33/33/33
A Priori	This distribution is based on mission planning projections of the objectives deemed to be most critical during LPR. This distribution does not include any real-time data. The baseline aim point is based on this weight distribution. Examples of weight distribution: 10/25/65, 31/ 43/26, etc.

Of the three operator actuator designs investigated, the hot keys concept is considered the best due to robustness of input (both hazard tolerances and objective weights are communicated to the AFM) and speed of use (one button push). When modeled in usage with the LPR task execution model presented by Chua and Major (2009), the hot keys demonstrated a clear advantage in operator execution time (0.82 seconds vs. 2.35 seconds using the dial) while offering great breadth in objective function selection. Although precision and authority are generally viewed as favorable, especially in manned spaceflight, allowing astronauts to set the tolerance and weight distribution in mid-flight adds complexity to the task. This complexity deepens if the input-feedback loop is not immediate. Therefore, the preprogrammed tolerances and weights of the hot keys reduce operator workload by limiting the options to the crew, while providing adequate authority to the crew.

The hot keys are particularly effective when used in tandem with the new proposed method to rectify the second bottleneck of multiple LAP evaluation. The previous presentation in LPR information limits the crew to a cross-examination of three LAPs (nominal and two alternatives) and the terrain information of each LAP. This limitation increases visibility, as the display becomes difficult to comprehend if all information is presented. Thus, the crew must routinely select, evaluate, and reselect which LAPs to closely examine. To facilitate this evaluation process, the new display presents all of the detailed terrain information of four LAPs (nominal and three alternatives) concurrently, with each hot key selection. However, utilizing the same information presentation as that suggested by Forest, Cohanin and Brady (2008) may not leave all of the information apparent and readily accessible to the astronauts.

To mitigate this problem of information presentation, especially with regards to representation and location on the display, the LPR display is simplified and reorganized to maximize the amount of information seen within a person's field of view. This philosophy manifests in the form of simple symbols, narrowing the amount of data processed by the astronaut, and grouping necessary information in centralized locations. The astronaut can focus more on the degree of quality, rather than determining whether a LAP is within the acceptable envelope. The following symbols are applied to the vehicle state and LAP terrain characteristics.

1. **Information superimposed on map of landing area.** The necessary information for LPR is located on one display, with vehicle state and terrain data overlaid on the synthesized map of the LIDAR data. This arrangement allows the astronaut to efficiently focus attention on one main location, minimizing eye movement (Wickens & Carswell, 1995).
2. **Fuel contour.** The Crew Office reported a fuel contour as critical information to execute the LPR task. This display utilizes a green ellipse superimposed on the photo of the landing area to divide the map into reachable and non-reachable fractions. All alternative landing sites are located within this ellipse. This ellipse also represents the relative fuel cost for each landing site. Landing aim points located closer to the center and along the major axis of this ellipse required less fuel than aim points located on the on the fringe and minor axis.
3. **Vehicle Footprint Dispersion Error (VFDE).** The VFDE is represented by a dashed purple circle proportional to the area encapsulated on the map. The diameter of the vehicle footprint plus errors is listed in a box in the lower half of this purple circle.
4. **Vehicle cross-sectional area.** The vehicle cross-sectional area is represented by a green circle located in the center of the VFDE circle. The size of this cross-section is equivalent to the area on the map. Superimposing

this information on the landing map also allows the operator to quickly determine the relative distance from hazards and the POIs.

5. **Terrain characteristics.** The terrain characteristics of each LAP are represented directly on the map. A modification of the four axis LAP information representation developed by Needham in 2008 is used for this study. Two of the four axes, slope and roughness margins, are utilized. The hazard and fuel margin axes are represented by other symbols. The slope and roughness margin information is displayed in the same manner prescribed by Needham (2009). Three marks along the axes are used to represent dangerous terrain characteristic (defined as, at the threshold), tolerable, and desired (far from the threshold). The arrows are desired to be as long as possible, hence representing a safe LAP.

6. **Points of interest.** The points of interest are represented in blue and proportional to the size of this area.

Circles and other geometric shapes can be used to represent lunar assets, or scientific spots of interest.

The final form of this display is illustrated in Figure 2. In this figure, the crater has been highlighted as the lone hazard. The nearest to POI hot key (labeled POI) has been selected, and the three alternative LAPs are shown. In accordance with the LPR algorithm formulated by Forest, Cohanin, and Brady (2008), the alternative LAPs are unique points and represent local optimums. Once the operator has chosen a final landing site, he can communicate this choice by pressing the identically labeled button in the lower left corner and immediately pressing the ARM button afterwards. At the conclusion of this action, the LPR task is formally finished.

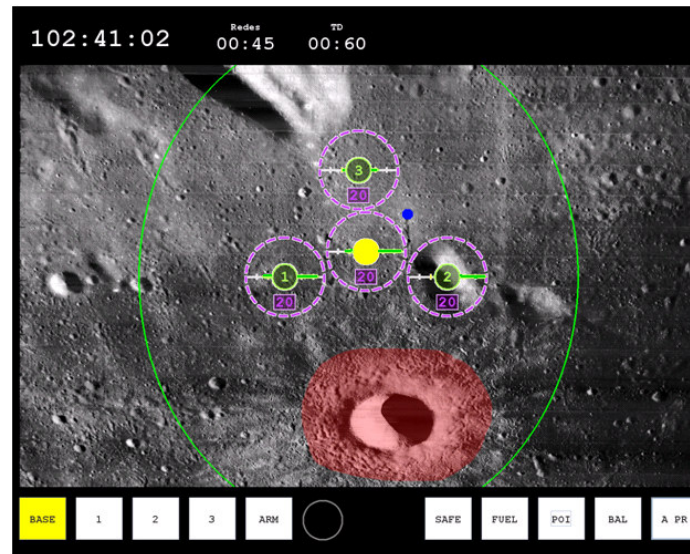


Figure 2. Landing point redesignation display.

Modeling Results and Discussion

The predictive task execution time model is applied to the full design space of potential lunar landing scenarios. These landing scenarios are defined by the number of hazards and points of interest defined in the previous section. The range of execution times across these scenarios is illustrated in Figure 3. The new LPR display design presented in this paper significantly expedites the LPR task. The recommendations, particularly with respect to LAP evaluation, dramatically reduce the time to perform the task by about 50% from the previous display. For the most feasible scenario, one POI, the LPR task is expected to conclude in approximately 31-36 seconds over the range of ITMs. The small variance with respect to the number of hazards is quite promising – denoting a near decoupling of task execution and terrain features. However, this analysis assumes a discrete number of hazards and does not examine hazard coverage of the landing area, or shape of the hazards.

The results from the predicted task execution time model are promising in the field of LPR display design. However, the models developed in this research are based on several key assumptions. The model assumes perfect human behavior. The operators used by the astronauts are completed the same time or less than those prescribed by Card, Moran, and Newell (1983) and by Olsen and Olsen (1990). This model also assumes the LPR algorithm is capable of presenting three alternative LAPs with every objective change. Finding three unique alternative LAPs may not be possible in extreme terrain conditions, and thus, the astronaut may make a quicker decision based on fewer points to consider. Lastly, this model assumes this is the first instance of LPR and first presentation of

processed LIDAR scan results and the astronauts are making a decision based on this singular opportunity. To understand and determine the accuracy of this model, further verification and validation is necessary.

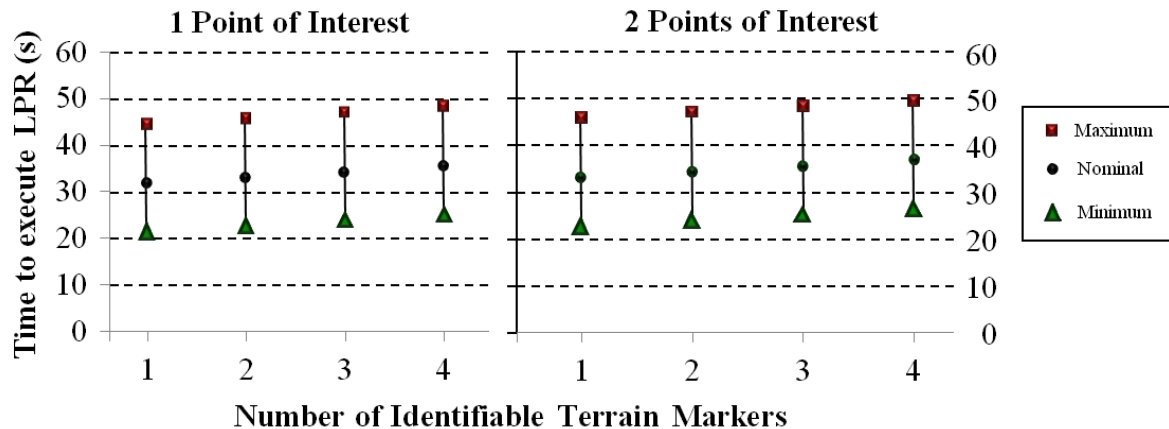


Figure 3. Landing point redesignation task execution times.

Conclusion

This paper presents the formulation of an improved landing point redesignation task model that accounts for the specialized behavior of expert decision-making. From this improved model, a predictive task execution time model was developed to estimate the minimum and maximum time range to complete the LPR task. The landing point redesignation display was also modified based on previously identified task bottlenecks. The hot keys concept was selected as the most effective operator actuator and the presentation of alternative landing site information was reorganized to focus on critical points. The task sequence model and cockpit display recommendations presented in this study provide a significant improvement in the time to execute LPR. For some scenarios, a time reduction of up to 50% is recorded. The most plausible scenario of one POI predicts an execution time of 31 - 36 seconds. While the results presented indicate effective LPR decision-making, the model developed in this study assumes perfect human performance. Further verification and validation is necessary, to quantify model accuracy.

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References

- Brady, T., Schwartz, J., & Straube, T. (2006, May). Operational Concept Description for the Autonomous Landing and Hazard Avoidance Technology (ALHAT). NASA Technical Report, ALHAT 2.0-002, Initial Release.
- Card, S., Moran, T., & Newell, A. (1983). *The Psychology of Human-Computer Interaction*. Lawrence Erlbaum Associates, Hillsdale, NJ.
- Chua, Z. & Major, L. (2009). Task Modeling for Lunar Landing Redesignation. InfoTech@Aerospace. In Press.
- Forest, L. & Cohanin, B. & Brady, T. (2008) Human Interactive Landing Point Redesignation for Lunar Landing. IEEE Aerospace Conference.
- Klein, G. (1998). *Sources of Power: How People Make Decisions*, MIT Press, Cambridge, MA.
- Manned Spacecraft Center: Apollo 12 Mission Report. MSC-01855. March 1970.
- Needham, J. (2008). Human-Automation Interaction for Lunar Landing Aimpoint Redesignation, S.M. thesis, Massachusetts Institute of Technology.
- Olsen, J. & Olsen, G. (1990). The Growth of Cognitive Modeling in Human-Computer interaction since GOMS. *Human-Computer Interaction*, 5 (2). 221-265.
- Smith, P., McCoy, C., & Layton, C., (1997) Brittleness in the Design of Cooperative Problem-Solving Systems. *IEEE Trans. on Sys., Man., and Cybernetics, Part A*. 27 (3)
- Wickens, C. & Carswell, C. (1995). The proximity compatibility principle: Its psychological foundations and its relevance to display design. *Human Factors*, 37, 473-494.
- Wiener, E. & Curry, R. (1980). Flight-deck automation: promises and problems. *Ergonomics*, 23 (10), 995-1011.